How Similar Is a Synchrotron to a Laser?

The laser-like properties of undulator radiation from the Advanced Photon Source (APS) were evaluated through the measurement of the degree of spatial coherence. A Young's two-slit experiment has been performed for the first time in the soft x-ray region. The measured high fringe visibility at a transverse slit separation up to100 μm demonstrates the laser-like behavior of the x-ray beam produced at APS.

Most of us are aware of how important lasers are, not only in scientific research but also in technology used in our everyday life. The CD player is just one of many examples where lasers are used unobtrusively in technology. It is now hard to imagine life without the laser. One of the key features of a laser that distinguishes it from standard light sources and makes it so useful is its coherence. Coherence refers to the "self-similarity" of the light and is usually associated with the brightness of the light source. One analogy of coherent light is to rows of soldiers all marching exactly in time and wearing exactly the same uniform, and so any portion of the group of soldiers (or light beam) appears very similar to any other portion.

The latest generation of synchrotron sources, such as the Advanced Photon Source (APS), have been designed and built to produce very brilliant, highly coherent light, particularly in the x-ray region. While a substantial amount of research has been done to push lasers to create light in the x-ray region, this has not resulted in a readily available device. At present, the only realistic method of producing intense coherent beams of short-wavelength light is with a synchrotron.

The hope and dream of creating highly coherent x-ray synchrotron sources is to make possible new and unique coherence-based experiments. These sources will enable the renaissance that occurred in visible-optics research with the introduction of the laser. The types of experiments that are possible and are already being conducted include scanning microscopy, interferometry, coherent scattering, and phase measurement. Third-generation sources achieve high brilliance and coherence through very low-emittance electron beams (beams with a very small size and traveling in the same direction) and by inserting into the electron beam a device known as an undulator. The undulator causes the electron beam to undulate or bend back and forth, and this produces very bright and coherent light.

In fact, two types of coherence can be defined—temporal (or longitudinal) and spatial (or transverse). Temporal coherence refers to how similar the light is at different points in time. Spatial coherence, on the other hand, refers to how similar the light is at different points in space. Temporal coherence is directly related to how monochromatic the light is, whereas spatial coherence relates to the size of the source emitting the light and the distance from the source. In our research, we have been concerned with measuring spatial coherence.

To realize the potential offered by highly coherent x-ray sources such as the APS, it is critical to characterize the spatial coherence of the beams they produce. Many experiments at the APS facility are now brilliance-driven and depend upon the coherence properties of the x-ray beams they use. However, little experimental work has been done on the detailed coherence properties of undulator beams due to the lack of a suitable means to efficiently measure the coherence profile.

The classic technique to measure spatial coherence is to perform a Young's two-slit experiment. This experiment, which was devised by Thomas Young in 1807, is achieved by placing two very narrow slits in front of the x-ray beam. The slits cause the light to split into two beams that diffract and interfere with each other. The degree to which the two beams interfere is a measure of the spatial coherence of the beam.

The experiments were performed at the 2-ID-B beamline of SRI-CAT at the APS. This is a beamline optimized to produce soft x-rays in the energy range of 1.0–4.0 keV. Figure 1 shows the positioning of the optical components in the horizontal plane along the beamline and the experiment apparatus. The coherent flux available at this beamline is 10^{10}–10^{12} photons/s/0.1% bandwidth; it is one of the most intense, continuously available sources in existence.

For these experiments, we fabricated an array of 7 slit pairs (10, 20, 50, 80, 100, 150, and 200 µm separation) in gold. The gold layer was 1.6 µm thick in the slit array. This very accurate lithography was also conducted in-house at the APS by our research team. The Young's interference fringes were measured by scanning an avalanche photodiode detector (APD) with a 5 µm slit placed directly in front of it, both of which were mounted on a translation stage.

In these experiments, we investigated the spatial coherence of a 1.1-keV x-ray beam by altering the exit slit located downstream of the beamline spherical-grating monochromator (see Fig. 1). Narrowing the exit slit has two effects. First, increased collimation of the beam increases the degree of monochromatization. Second, the size of the beam is reduced as sections of the beam are removed.

The degree of spatial coherence $|\mu_{12}|$ is given by the fringe visibility of a Young's experiment. This is

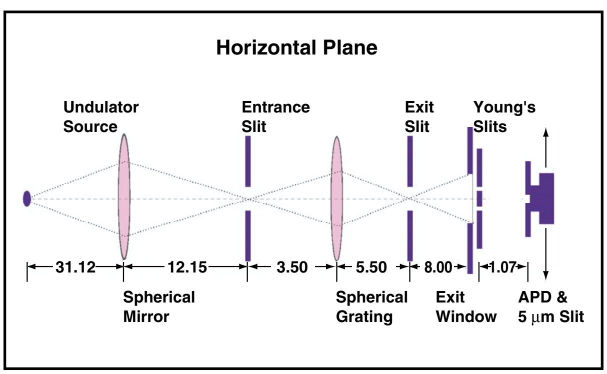

FIG. 1. The 2-ID-B beamline and Young's experiment at the APS showing beamline optics depicted as thin lenses in the horizontal plane. Distances shown are in meters. The total distance from the undulator to the experiment is 60.3 m.

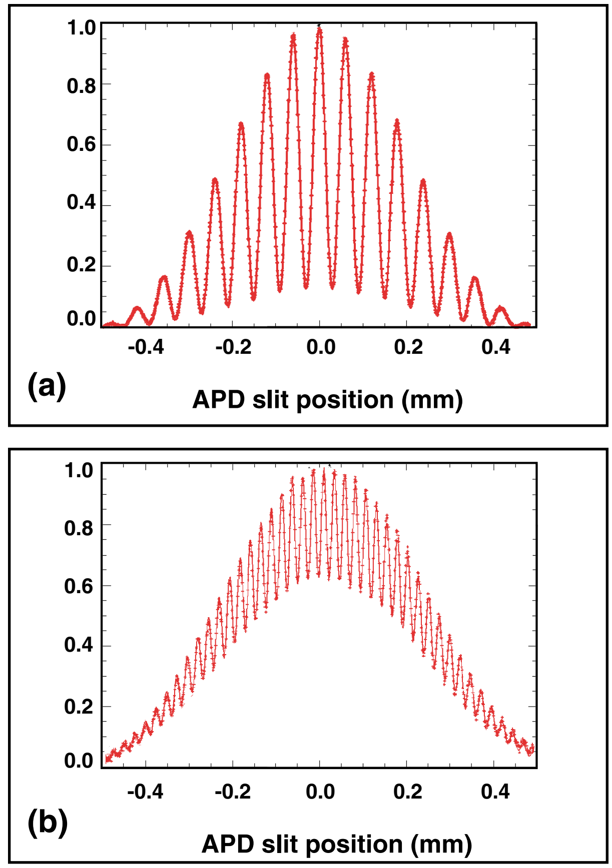

FIG. 2. Young's two-slit diffraction pattern for 1.1-keV x-rays from the 2-ID-B undulator beamline: Young's slit separation of (a) 20 µm and (b) 50 µm. Diffraction profiles were obtained with an avalanche photodiode detector. The data are represented with crosses, and the solid line is a theoretical fit to the data used to determine the spatial coherence.

essentially a measurement of how well the light interferes with itself, and therefore how similar it is at different points in space. Fringe visibility is simply the ratio of the brightest part of a fringe (I_{max}) to the darkest (I_{min}), or:

$$\text{visibility} = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} = |\mu_{12}|.$$

If we compare the graphs in Figs. 2a and 2b we can see the difference in fringe visibility as the slits are separated by larger distances. In Fig. 2a, where the two slits were separated by 20 µm, the fringe visibility is high, about 80%, whereas, when the slits are separated by 50 µm, the fringe visibility drops to 25%.

A complete investigation of spatial coherence involves measuring the fringe visibility for a range of Young's slit separations. The degree of coherence for

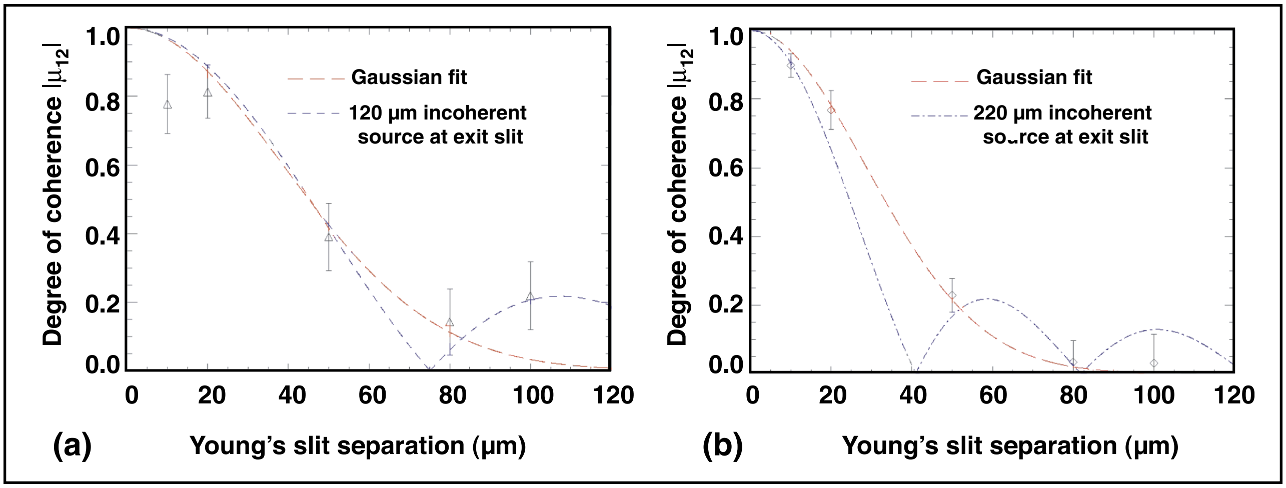

FIG. 3. Spatial coherence measurements for two exit-slit widths: (a) 100 μm and (b) 200 μm.

the various Young's slit separations is plotted in Fig. 3 for two exit-slit settings. The results for various Young's slit separations can also tell us something about the size and shape of the undulator source, providing important feedback for improving the characteristics of the synchrotron ring. In our research we compare our experimental results with models predicting the coherence that should be produced by various undulator source sizes and shapes. The predicted coherence was found to be in good agreement with the experimental results.

A complete measurement of the coherence function requires the degree of coherence to be determined for the full range of slit separations and locations over the two-dimensional beam cross section. This is an extremely time-consuming and therefore impractical experiment using Young's slits; thus, a more efficient method for determining coherence properties of x-ray radiation is required. This is the focus of our continuing research at sector 2 of the APS.

In conclusion we can say that, under the right conditions, the APS synchrotron is similar to a laser. We have shown this by performing Young's two-slit experiments for the first time in the soft x-ray region. The radiation at the exit of the beamline is shown to have very high spatial coherence at transverse separations up to 100 μm.

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